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Research Article

Influence of Carpal Tunnel Pressure on Finger Kinematics: A Biomechanical Study

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Received: December 08, 2021; **Published:** March 10, 2022

Abstract

Background: Carpal tunnel syndrome is an entrapment neuropathy which arises from an increased carpal tunnel pressure (CTP), which compresses the median nerve and leads to symptoms such as tingling, numbness, and pain in the affected hand. Previous studies have examined the effect of this pathology on median nerve kinematics; however, a possible association between CTP and finger join kinematics has not been well established.

Purpose: This study aims to measure the effect of an increased CTP on finger kinematics and energy at the metacarpophalangeal (MCP) joint as the flexor digitorum superficialis and flexor digitorum profundus tendons undergo flexion from a neutral position.

Methods: Digit kinematics were tested in seven cadaveric hands, harvested from cadaveric male subjects (mean age 71 ± 12). Index fingers were selected for measurement of tendon force and finger range of motion with imposed carpal tunnel pressures. A pressure regulating device with a balloon and sphygmomanometer attached were used to modify the CTP. Each hand was secured to a rigid frame with an intramedullary rod passing thought the metacarpus. Both flexor tendons were sutured to cords connected to two stepper motors and were driven at a constant rate. Motor actuation, joint movement, and kinematics were recorded from this initial posture using a custom stereovision system. Initial control experimentation was repeated after partial and complete releases at the imposed pressures.

Results: When both the FDP and FDS tendons were corded to the motor and pulled, the maximal flexion angle was 52 ± 14° at 0 mmHg with the fully intact ligament, slightly decreased to 50 ± 14° at 120 mmHg. After partial release, the joint exhibited flexions of 56 ± 17° at 0 mmHg and 54 ± 15° at 120 mmHg. At full release, the maximum flexion angle was 55 ± 18° with no balloon.

Discussion: The results showed an increased intracarpal pressure did not have a statistically significant impact on the maximal flexion angle at the MCP joint, however, a trend towards a reduction in angular displacement for the MCP joint was observed. Additionally, the study showed that integrity of the flexor retinaculum may have an influence on the range of motion of the index finger under various CTPs.

Keywords: *Carpal Tunnel Syndrome; Biomechanics; Kinematics; Median Nerve; Hand Surgery*

Abbreviations

CTP: Carpal Tunnel Pressure; CTS: Carpal Tunnel Syndrome; MCP: Metacarpophalangeal; FDP: Flexor Digitorum Profundus; FDS: Flexor Digitorum Superficialis

Introduction

The hand is among the most intricate structures of the human body. The synchronization of ligaments, muscles and tendons, and nerves allow for the delicate motions required for music, typing, and other precision movements. These structures are vastly interconnected, and any imbalance in this network that stabilizes structures and allows for movement may result in detrimental outcomes for those who require the highest levels of dexterity. Additionally, gross motor movements at the hand, essential for functional life in even the average patient, including screwing, torqueing, pinching and grasping, can also be affected in extreme disruptions of the hand. These essential actions are often repeated hundreds, if not thousands of times over the course of a single day, so even a small disruption in function or efficiency can result in significant deterioration in patient quality of life.

Carpal Tunnel Syndrome (CTS) is the most common entrapment neuropathy, affecting 3.8% of the adult population [1]. Gaining a deeper understanding of CTS has become critical in the face of rising healthcare costs, with reports showing that the average lifetime cost of CTS per worker, including lost productivity, is approximately $30,000 [2]. The underlying disease mechanism is an increased carpal tunnel pressure (CTP), occurring secondary to either a decreased carpal tunnel size or an augmentation in the volume of its fluidic contents and its inflammatory conditions [3,4]. As a result, the median nerve becomes compressed, inducing symptoms such as tingling, numbness, and pain [5,6]. Previous work by Harris-Adamson et al. demonstrated that forceful occupational hand exertion activities were significantly associated with increased incidence of CTS [7]. Other work by Palmer., *et al*. demonstrated that risk factors for CTS are repetitive and forceful finger movements [8], particularly in extreme wrist postures.

Carpal tunnel syndrome is typically a clinical diagnosis, but adjunctive testing may also be used. The median nerve compression test involves pressing on the transverse carpal ligament and looking for the onset of symptoms within 30 seconds. It features a relatively poor sensitivity of 64% and a specificity of 83%. Tinel's sign, which involves tapping instead of held compression over the carpal tunnel, features similar outcomes at 36 - 50% sensitivity and 77% specificity [9]. Perhaps the most popular exam for carpal tunnel syndrome is Phalen's maneuver. This exam requires patients to flex their wrists to 90° and push the dorsal surfaces of the hands together for 60 seconds. Median nerve symptoms indicate a positive test, but the exam only contains a sensitivity of 57 - 68% and a specificity of 58 - 73% [9]. Adjunctive diagnostic measures include ultrasonography, which features a 87.3% sensitivity and a 83.3% specificity for CTS, and electrodiagnostic studies, which display a lower sensitivity of 56% to 85%, but a higher specificity of 94% to 99% [9].

As there is no single "gold-standard" test for diagnosing CTS; previous studies have shown that existing screening tests produce nearly 50% false positive results [2]. This cohort of misdiagnosed patients is likely in turn responsible for the nearly 45% failure rate for CTS release surgeries [2]. Additionally, previous case series show that symptoms of CTS can be often misdiagnosed for other neurological disorders such as cervical radiculopathy, brachial plexopathy, and syringomyelia, resulting in poor surgical outcome [5,10].

Manual dexterity may be profoundly affected in patients suffering from CTS [11,12]. Various studies have explored the association between impaired nerve function and finger joint kinematics, demonstrating a reduction of pinch performance and angular motion [13,14]. Other studies have focused on the impact of an increased intra-carpal tunnel pressure on median nerve and tendon kinematics, using a balloon catheter in the carpal tunnel of cadaver hands to artificially increase pressure [15,16]. Bay., *et al*. demonstrated that CTP had no statistically significant effect on the ratio of median nerve to flexor tendon excursion, on median nerve strain, or on grip strength after applying pressures up to 90 mmHg. As a result, they concluded that CTP had no effect on median nerve kinetics or kinematics [15]. However, with a neutral wrist position, there was a tendency towards a reduction in grip strength with increased pressure values. Zhao et al. showed that CTP had a direct positive impact on gliding resistance, meaning that an increase in pressure induced an increase in gliding resistance [16]. Additionally, Kociolek., *et al*. demonstrated a greater increase in frictional flexor tendon work in wrist flexion when compared to wrist extension [17].

To date, the possible association between CTP increase and an alteration in finger joint kinematics as well as energy exerted by the tendons during finger flexion and extension has not been investigated. Additionally, previous studies focused on the effects on a singular muscle, while one arm of this investigation features the action of FDP and FDS simultaneously, which may better mirror physiologic flexion of the digits. Coupling nerve pressure to finger joint kinematics and energy required may be a useful diagnostic tool to screen patients for examination.

Aim of the Study

This work aims to analyze the alteration of these values in relation to CTP. To achieve this goal, the experiments will not only be conducted with an intact flexor retinaculum, but also with a partially and fully released ligament.

Methods

Experimental setup

A custom-built pressure device was first designed to apply and regulate CTP. The device consisted of a rubber latex balloon connected to a tube by vinyl electrical tape. A plastic stick with blunted edges was placed inside the balloon connected to the tube to facilitate the implantation of the balloon into the carpal tunnel of the cadaver. Distally, the tube was connected to a metal t-valve, with the two ends of the t-valve connected to a sphygmomanometer, with pressure range of 0 to 300 mmHg, and a sphygmomanometer bulb (Figure 1). Pressure was increased inside of the balloon via air injection and was measured by the sphygmomanometer.

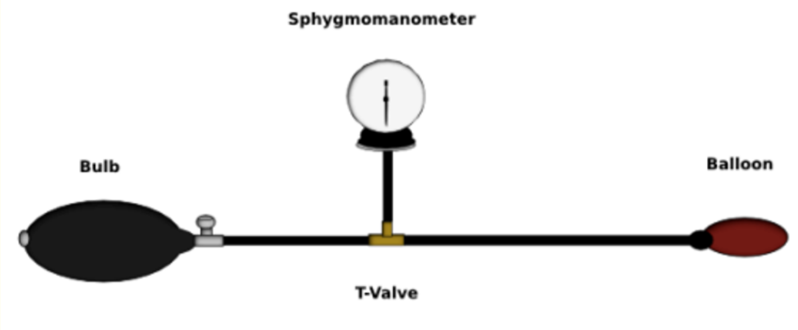

Figure 1: *Pressure regulating device with balloon and sphygmomanometer attached.*

In addition, a point and motion based analysis system was built to capture digit motion. The system utilized two cameras and a custom-built stereovision software system in LabVIEW (National Instruments, Austin, TX, USA) to track digitized points in space and capture motion of objects in real-time. First, both cameras were calibrated utilizing algorithms obtained from the Camera Calibration Toolbox for

MATLAB. The focal length, principal point, skew angle, distortion, and the pixel error of each camera were obtained after calibration of the cameras. In the study, the system was used to track eight markers approximately 5 mm in diameter on the radial aspect of the index finger.

The driving system was controlled through an Arduino Mega 2560 microcontroller connected to two identical drivers, which in turn controlled two motors (Figure 2). The Arduino was connected to a force sensor (Mark-II) and with a USB interface to a computer. In addition, the mechanical driving system of two identical stepper motors was used to pull the finger tendons. The motors activated two spools which rotated with a constant velocity. A cord was attached to each spool and connected through a force sensor to the tendon of the index finger. The second spool was used only if both the FDP and FDS tendons were pulled simultaneously.

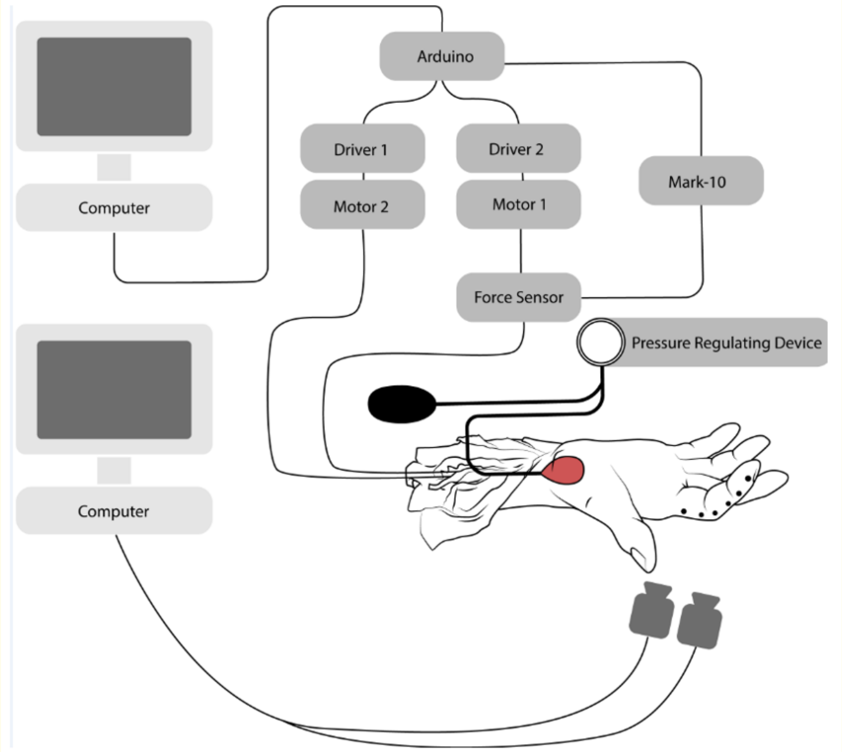

Figure 2: *Schematic drawing of the experimental setup with the mechanical driving system. Cadaver hand is also shown affixed to the apparatus with markers on the radial aspect of the index finger.*

The excursion of the tendons, as well as the velocity of finger movements, were determined and implemented into LabVIEW. Subsequently, the data was transmitted to the microcontroller which calculated the corresponding pulse rate. The displacement of the spool, time, and the applied force to pull the tendons with a constant velocity were recorded with a frequency rate of 60 values per second.

Preparation of cadaveric specimens

Human cadaver hands used in this study were made available through the UIC Department of Orthopaedics. Specimens were thawed overnight to room temperature prior to testing. Once the cadaveric specimens were thawed, the Flexor Digitorum Longus (FDL), Flexor

Digitorum Profundus (FDP) and Flexor Digitorum Superficialis (FDS) tendons were identified by pulling the different flexor tendons manually and observing the resulting hand movement. The tendons of the index finger were marked. Subsequently, the first Steinmann pin was drilled with a pin driver through the metacarpal bones. The pin was drilled parallel to the MCP joint and approximately one-third distal of the diaphysis of the metacarpal bone. A second pin was drilled through the radius and the ulna approximately 6.5 cm proximal to the wrist crease. To guarantee that the Steinmann pin did not alter the finger joint kinematics, each tendon was pulled manually and hand movement was observed. After verifying that the hand did not undergo any harm, the hand was affixed to the apparatus volar side up and in neutral wrist flexion. Eight digitized points were used on the radial aspect of the hand for measurements, indicated by dots shown in figure 2 and 3. In addition, two dots were stained on each phalangeal bone and on the metacarpal bone of the index finger.

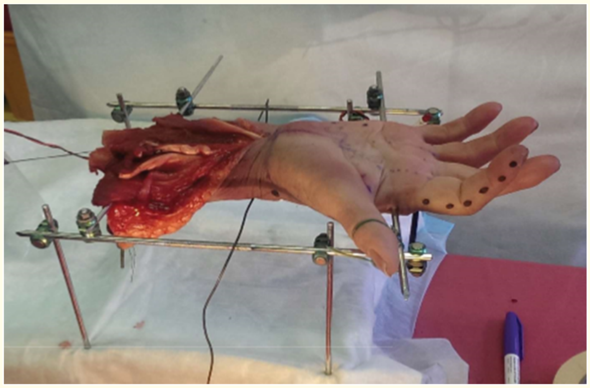

Figure 3: *Cadaver hand affixed to the apparatus with markers on the radial aspect of the index finger indicating location of the digitized points.*

Cameras were then placed so that all digitized points would be detected during finger movement. After attaching the tendon to the force sensor, the digits were extended and image was taken. The image was then opened in the custom-designed software and each marker location was determined by picking the markers manually from proximal to distal. The border of the starting condition of each marker was saved to guarantee the same starting point within all experiments. Finally, the excursion for each tendon was determined without damaging the surrounding soft tissue.

Experimental procedure

Digit kinematics was tested in seven cadaveric hands, harvested from cadaveric male subjects with mean age of 71 ± 12. The index fingers were selected to simplify measurement of tendon excursion, tendon force, and finger range of motion with imposed carpal tunnel pressure. In the first experimental series, the FDS tendon of the index finger was corded to the spool of the first motor. In addition, the excursion value and the pulling velocity were entered into the custom-designed software. The first series of experiments were conducted with an intact flexor retinaculum. Afterwards, the balloon was inserted inside the carpal tunnel in order to prevent incorrect placement. The experiments were then repeated without applying any pressure in order to investigate the impact of the balloon itself. Subsequently, the pressure value inside the balloon was increased to 40 mmHg, 60 mmHg, 80 mmHg, 100 mmHg, and 120 mmHg. The balloon was kept in place manually throughout the experiment.

The computer-controlled motor pulled the tendon with a constant velocity of 2 mm/sec through a full range-of-motion starting from an at-rest position (neutral extension) to maximal flexion. During each set of experiments, joint movements and kinematics were recorded by the custom stereovision system while the force sensor measured the applied force.

In the second series of experiments, the FDP tendon was corded to the motor. All experiments were repeated as described above. In the third series of experiments, both the FDP and FDS tendons were attached to the motors. To pull both tendons together, the FDS tendon was connected to the first motor, while the FDP tendon was connected to the second motor. Only the FDS tendon was attached to a force sensor. In order to establish the influence of an intact flexor retinaculum on finger joint kinematics, all experiments were repeated with a partially released ligament. The flexor retinaculum was dissected proximally, with only half of the ligament cut and the same amount of skin dissected. To be consistent with the previous experiments, the exerted force value of the FDS tendon was measured when both tendons were pulled simultaneously. To calculate the change in rotation of each digit, the initial angle was subtracted from every angle value. The same angle value was subtracted in order to have the same starting point for each condition. To be able to compare the intact ligament with the partially and fully dissected ligament, a new starting angle was defined for a pressure value of 0 mmHg. Subsequently, each series of trials was averaged to mitigate random errors in measurement. To eliminate noise, the results were filtered by a polynomial equation.

Results and Discussion

To examine the effect of finger joint kinematics based on CTP, the maximum flexion angle at the MCP joint was measured when both the FDP and FDS tendons were corded to the motor and pulled. In the configuration with the fully intact ligament, the maximal flexion angle was 52 ± 14° at 0 mmHg, slightly decreased to 50 ± 13° at a pressure of 60 mmHg and featured an angle of 50 ± 14° at 120 mmHg. After partial release, the joint exhibited flexions of 56 ± 17° at 0 mmHg, 52 ± 16° at 60 mmHg, and 54 ± 15° at 120 mmHg (See figure 4). At full release, the maximum flexion angle was 55 ± 18° (with no balloon). As indicated in figure 4, there was high variability between angles in different cadaver specimens. Figure 5 shows a comparison between the minimum angle values when the flexor retinaculum was intact to the maximum angle values of the partially released and fully released flexor retinaculum at all pressures.

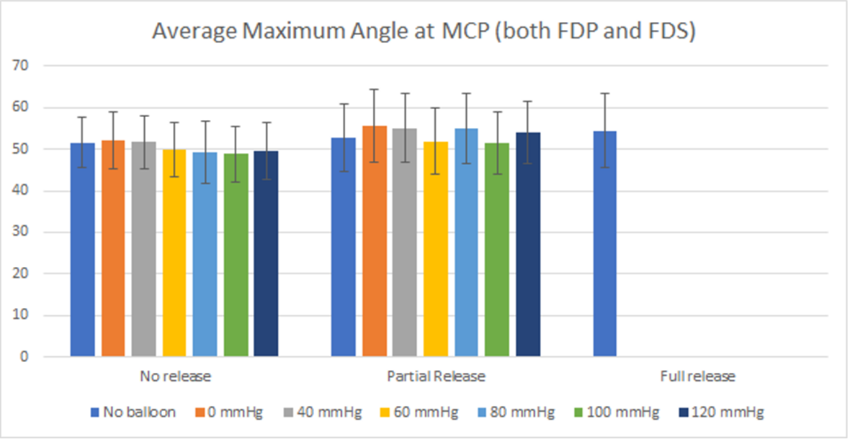

Figure 4: *Average maximum flexion angle at the MCP joint measured in degrees for the intact tendons, partially released, and fully released tendon when both the FDP and FDS were corded to the motor and pulled.*

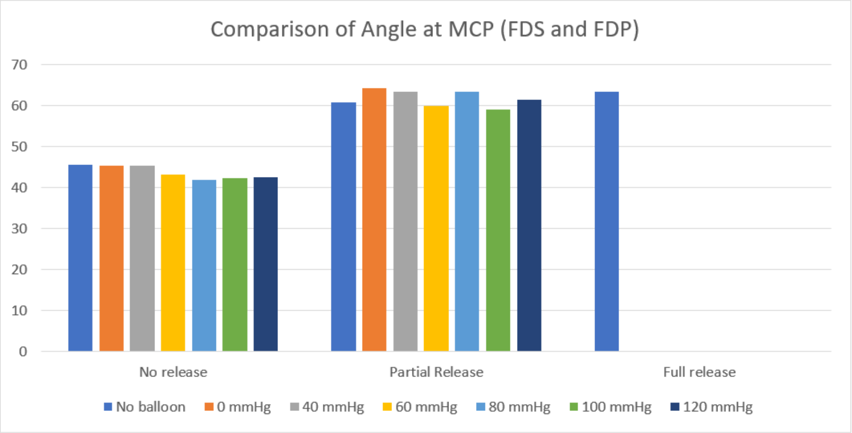

Figure 5: *Comparison of the angle at the MCP joint between the lower bound of the intact tendon and upper bound of the partially released and fully released tendon (both FDS and FDP corded to the motor and pulled).*

When solely the FDP was pulled, the MCP had measured flexion angles of 47 ± 16° at 0 mmHg for the intact retinaculum and 51 ± 14° for the partially released retinaculum. At 120 mmHg, flexion angles were measured at 48 ± 16° and 49 ± 15° for the fully intact and partially release tendons, respectively (Figure 6). At full release, the maximum flexion angle was 55 ± 17° (with no balloon). Figure 7 shows a comparison between the minimum angle values when the flexor retinaculum was intact to the maximum angle values of the partially released and fully released flexor retinaculum at all pressures when only the FDS tendon was pulled.

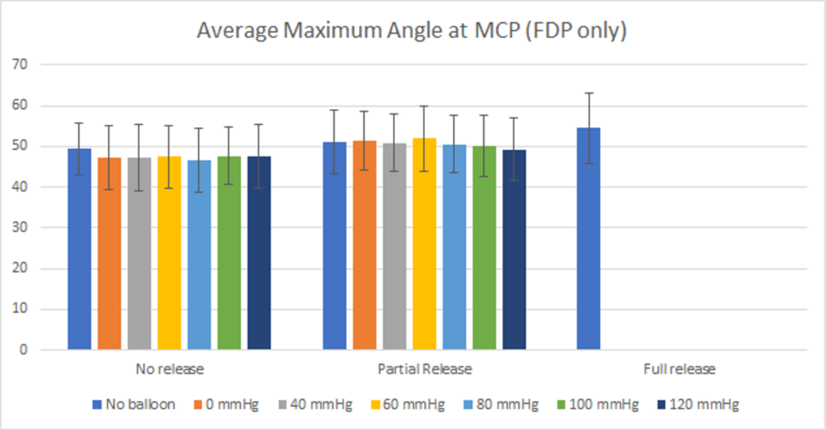

Figure 6: *Average maximum flexion angle at the MCP joint measured in degrees for the intact tendons, partially released, and fully released tendon when only the FDP was corded to the motor and pulled*

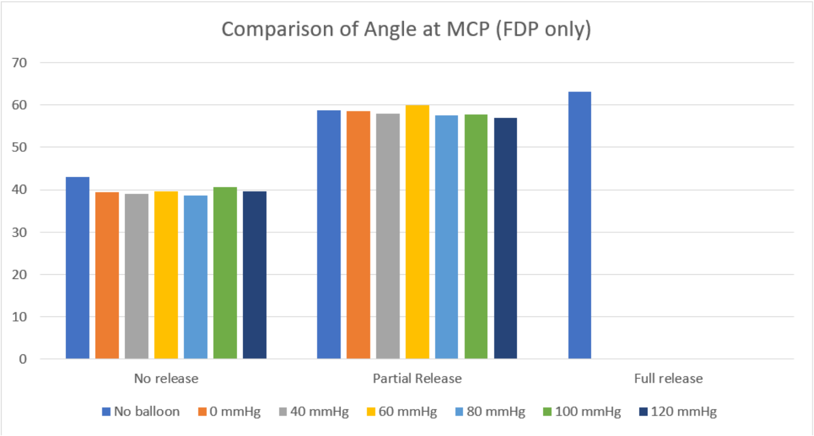

Figure 7: *Comparison of the angle at the MCP joint between the lower bound of the intact tendon and upper bound of the partially released and fully released tendon (FDP only corded to the motor and pulled).*

When solely the FDS was pulled, the MCP had measured flexion angles of 54 ± 15° at 0 mmHg for the intact retinaculum and 58 ± 16° for the partially released retinaculum. At 120 mmHg, flexion angles were measured at 55 ± 16° and 55 ± 15° for the fully intact and partially released tendons, respectively (Figure 8). At full release, the maximum flexion angle was 57 ± 17° (with no balloon). Figure 9 shows a comparison between the minimum angle values when the flexor retinaculum was intact to the maximum angle values of the partially released and fully released flexor retinaculum at all pressures when only the FDP tendon was pulled.

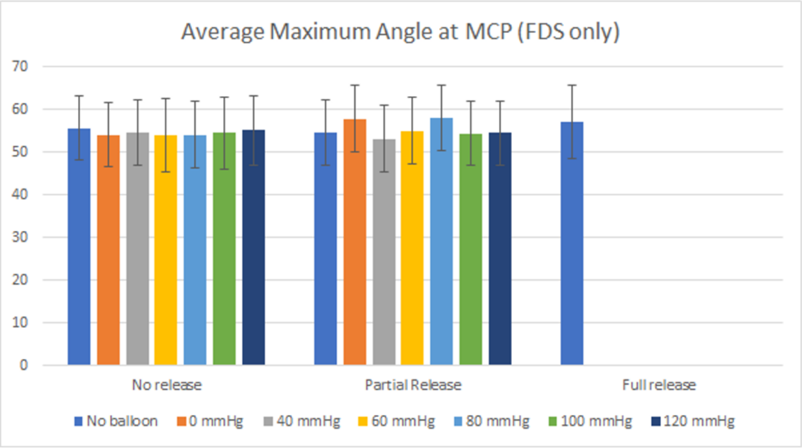

Figure 8: *Average maximum flexion angle at the MCP joint measured in degrees for the intact tendon, partially released, and fully released tendon when only the FDS was corded to the motor and pulled.*

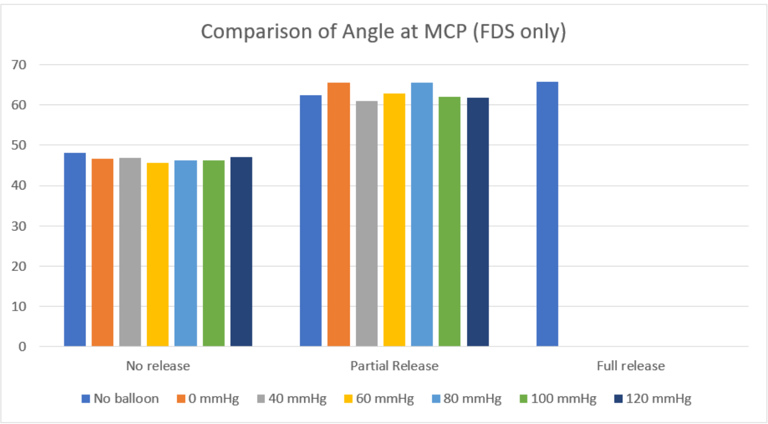

Figure 9: *Comparison of the angle at the MCP joint between the lower bound of the intact tendon and upper bound of the partially released and fully released tendon (FDS only corded to the motor and pulled).*

For each of these configurations (FDP and FDS, FDP only, and FDS only), the average maximum angle increased slightly in the partially released and fully released flexor retinaculum when compared to the fully intact ligament at equal balloon pressures. When comparing the lower bound of the intact flexor retinaculum to the upper bound of the partially released and fully released tendon, there is a significant increase in the angle at the MCP join for all values of CTP.

In addition to finger kinematics, the energy exerted by the tendons was also measured as CTP was increased. When both the FDS and FDP tendons were pulled and the flexor retinaculum was not released, the average energy required was 0.058J ± .003 when 0 mmHg was applied, increasing to 0.62J ± 0.02 when 120 mmHg was applied. In the partially released ligament, energy increased from 0.073J ± 0.046 to 0.072 ± 0.046J at 0 mmHg and 120 mmHg respectively (Figure 10). When the ligament was fully released, the average energy required was 0.071J ± 0.042.

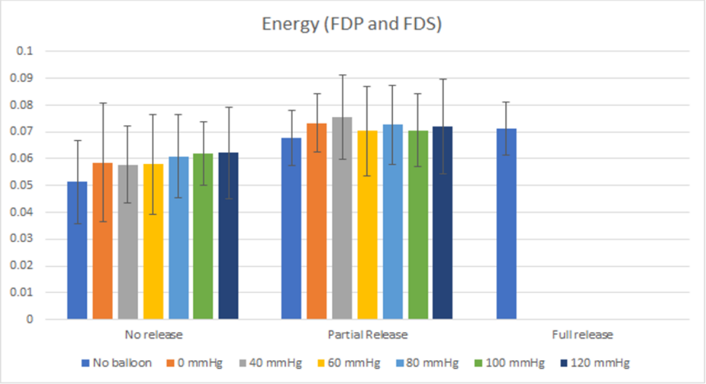

Figure 10: *Energy measured (J) when both the FDP and FDS were pulled for the fully intact, partially released, and fully released ligaments.*

The average maximum flexion angle at the MCP joint was measured at varying pressures when the FDP and FDS tendons were pulled in tandem, when only the FDP tendon was pulled, and when only the FDS tendon was pulled. As a trend, this study shows that carpal tunnel release may lead to an increase in range of motion (ROM) of the MCP joint as measured by the maximum flexion angle. In all three experimental setups, the average maximum flexion angle increased when the flexor retinaculum was released compared to the fully intact retinaculum.

In addition, as a general trend, the data in the fully intact retinaculum showed that the flexion angle typically decreased as pressure increased from 0 mmHg to 120 mmHg. However, in the partially released ligament, flexion angles were more variable as pressure was increased using the balloon. This can likely be explained by the effect of the balloon sliding into the space created by the partial cut in the ligament, thereby affecting the maximum flexion angle at the MCP joint. Other limitations include the small magnitude of changes in angle between trials. This may be due to the physical limitations of the motor used to pull the tendons, as a more powerful motor would likely result in more significant changes in the angle as pressure in the carpal tunnel increased. In addition, patients suffering from CTS may exhibit a pathological alteration of the structures within the carpal tunnel [18], which can alter the kinematics of the tendons in comparison to normal.

Patients suffering from carpal tunnel syndrome often exhibit significant problems with grip strength, manual dexterity, and numbness and paresthesia in the fingers and hand as their condition progresses [6]. There are many studies that explore the mechanisms by which median nerve compression in the carpal tunnel produces these physiologic pathologies [15,19]. However, the presence of the flexor pollicis longus (FPL), flexor digitorum profundus (FDP), and flexor digitorum superficialis (FDS) in the carpal tunnel leads to the likelihood that there are also mechanical disturbances related to increased intracarpal pressure that contribute to CTS symptoms, especially those related to manual dexterity and grip strength.

The impact of CTS on grip strength remains an area of controversy in the literature. There are many studies that show CTS patients exert significantly larger grip force while holding objects in their hands than controls. Some studies referred to this increased grip force as an “increased safety margin”, where CTS causes patients to hold objects with a much higher forces as a compensation for decreased tactile feedback [20-22]. Other studies, however, have shown similar safety margins between CTS and control [23,24]. This variability in study results may be explained by a recent study [25] demonstrating grip instability and inaccuracy in patients with CTS, where maintaining consistent grip force for the same action was significantly more challenging [25]. However, the literature is in general agreement about a decrease in maximal grip strength in patients with CTS [26,27]. Studies have shown that this reduction in grip strength is significantly correlated to median nerve blockade, which reduces intrinsic muscle performance (responsible for flexion of the MCP) [28]. This decrease in grip strength may be partially explained due to the decrease in ROM as a result of flexion of the FDS and FDP joints as CTP increases, thus resulting in decreased grip force.

To be able to correlate findings of this study to real-world values, clinically relevant pressure values were applied to the carpal tunnel using the balloon. Previous studies in human and animal subjects indicate that CTP above 20 mmHg for a sustained time period can result in significant complications for nerve conduction and vascular flow [29]. In a study using canine subjects, pressures of 30 - 40 mmHg resulted in partial nerve conduction blocks, with pressures above 50 mmHg resulting in complete conduction blocks [30]. In another study, Gelberman., *et al*. demonstrated that pressures above 40 mmHg result in decreased action potential amplitude and numbness; after 240 minutes of pressure above 40 mmHg, subjects also experienced altered vibratory perception [31]. Thus, detecting small pressure increases above 20 mmHg in the carpal tunnel are clinically significant for preventing the typical symptoms of CTS and for potentially preventing irreparable nerve damage.

Conclusion

Typically, diagnosis of CTS is made by considering clinical symptoms and/or electrophysiological testing such as nerve conduction studies. However, clinical symptoms typically demonstrate low sensitivity and specificity, which may lead to misdiagnosis of the condition [2]. Recent studies also indicate that additional decision making tools would be beneficial for ensuring diagnostic and treatment decisions for CTS that are aligned with patient preferences [32]. Changes in the kinematics of finger/muscle movement of the hand may provide a more cost-effective screening tool for the potential diagnosis of CTP and useful for guiding treatment choice.

Acknowledgements

We thank Sarah Davis for her help in providing figures and illustrations for this work. We would also like to show our gratitude for Susan King for her assistance in preparing cadavers.

Conflict of Interest

The authors declare no financial interest or conflicts of interest.

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